Renewable Energy 141 (2019) 390–401

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Estimating the impact of climate change on wind and solar energy in Brazil using a South American regional climate model

Pieter de Jong*, Tarssio B. Barreto, Clemente A.S. Tanajura, Daniel Kouloukoui, Karla P. Oliveira-Esquerre, Asher Kiperstok, Ednildo Andrade Torres

Federal University of Bahia, Universidade Federal da Bahia, Brazil

ARTICLE INFO

Article history:
Received 28 October 2018
Received in revised form
14 March 2019
Accepted 15 March 2019
Available online 20 March 2019

Keywords:
Climate change
Wind power
Solar radiation
PV
Renewable energy

ABSTRACT

In the coming decades, higher temperatures, significantly reduced rainfall and changing wind speeds are projected for various semiarid regions due to Global Warming. Hydroelectric production in Brazil's São Francisco basin has already declined as a result of regional climate change, however less is known about the impacts on other renewable resources. The objective of this study is to estimate the impact of climate change on Brazil's solar and wind energy resources. Data from three different downscaled global climate models is used to estimate the percentage changes in average solar radiation and wind speed by the 2030s and 2080s under high emissions scenarios in comparison to baseline data from the end of the 20th century. Results show that due to climate change, solar energy potential could increase slightly at solar power plant locations in the NE and Southeast regions. Wind energy potential is projected to increase substantially across most of Brazil and at some wind farm locations wind power generation could increase by more than 40%. Despite some inconsistencies between the long-term projections from the 3 different climate models, the results of this research are important in the context of regional climate change and renewable energy resource planning.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

While climate change mitigation will require the use of more renewable energy, renewable resources can be impacted by various aspects of regional climate change. As well as impacting air temperature, climate change is already impacting rainfall, wind speeds, storm intensities and drought frequencies as well as various aspects of agriculture and the environment. Climate change projections indicate that there will be diminishing precipitation and more severe droughts in Northeast and Northwest Brazil, Southwest Australia, Southwest USA, the Mediterranean [1] and various regions in Africa [2]. In particular, streamflow in semiarid regions, such as the Brazilian Northeast (NE), is vulnerable to more frequent and intense prolonged droughts due to climate change [3].

However, the impact of climate change on other types of renewable resources in the South American region requires more in-depth research. Therefore, the objective of this study is to determine the impact of climate change on solar and wind energy resources in Brazil.

1.1. Originality of this study compared to previous works

The only study that investigates the impact of climate change on both wind and solar resources in a single region was conducted by Fant et al. [4] who found that these renewable resources would mostly likely remain relatively unchanged until 2050 in southern Africa. Other recent studies (summarised below) tend to focus on either wind or solar resources, but not both. For example, using an ensemble of Coupled Model Inter-comparison Project Phase 5 (CMIP5) global climate models Carvalho et al. [5] found that wind power density is projected to decline over Western and Eastern Europe, but increase over the Baltic Sea region.

Typically, analysis in previous studies makes use of monthly [5] or 3 monthly [6] time series projections, which can give some insight into seasonal wind speed variations. However, hourly or

* Corresponding author.
E-mail address: pieterj@ufba.br (P. de Jong).

https://doi.org/10.1016/j.renene.2019.03.086
0960-1481/© 2019 Elsevier Ltd. All rights reserved.

even 3-h wind speed variations, which are important when estimating wind power generation, cannot be accurately ascertained from average monthly or seasonal data.[1] Climate change consequences on wind power should be assessed using the frequency distributions of projected wind speeds rather than just average seasonal wind speed values [7]. Therefore, in order to overcome this knowledge gap, the present study uses 3 global climate models with a temporal resolution of 3 h. Additionally, the data is downscaled using a regional climate model with a horizontal resolution of 20 km in order to more precisely estimate future wind speeds at actual wind farm locations. Previous studies that project future wind speeds and wind power density typically focus on large regions and use models with coarse horizontal resolutions that may not capture climate variations that occur on a local scale. Yet long-term trends in average wind speeds can vary substantially from one location to another in the same country [8,9].

Changes in the wind speed probability distribution could result in inefficiencies between the optimal design of a wind turbine's power curve and its wind resources [7]. Therefore, the finer horizontal and temporal resolution of the present study compared to previous studies, allows for more accurate estimates of future wind power density. As well as calculating the changes in wind power density, the present study also uses a typical wind turbine power curve to estimate changes in the actual wind power capacity factor at 4 wind farm locations. Furthermore, in a novel approach, the Weibull shape factor, *k*, is also estimated for different climate periods at 4 unique locations in Brazil in order to assess any changes in the probability distribution of wind speeds at each location. This is the first study of its kind to apply these types of analyses to long-term wind speed projections.

There are only a few studies that assess the impact of climate change on solar resources. Wild et al. [10] observed that from the 1950s until about 1985 there was a decrease of approximately 4–6% in surface solar radiation globally due to aerosol pollution, although, since the late-1980s solar radiation has increased, particularly over the northern hemisphere, Australia and Antarctica. This trend reversal was possibly due to the implementation of clean air regulations and the decline in Eastern European economies at the end of the 1980s [10]. However, the authors specifically state that over South America there is a lack of sufficient accurate data to reach a robust conclusion. In another study, Wild et al. [11] found that photovoltaic (PV) output is projected to decrease in large parts of the world, including most of Asia, Northeast Africa and most of North America, as a result of decreasing surface solar radiation and rising temperatures. Nevertheless, increasing surface solar radiation and PV output are indicated for most of Europe, Southeast USA, Australia and Southeast China. The study used several CMIP5 climate models and focused on various regions expected to have large-scale solar power plants with the notable exception of South America. One of the difficulties with the Wild et al. [11] study and especially in a similar study by Huber et al. [12] is that the global climate models use very coarse horizontal resolutions (up to 400 km) which do not allow for robust conclusions on regional and local scales. One of the few studies that assess the impact of climate change on future solar irradiation on a local scale was conducted by Burnett et al. [13]; however, the study only focussed on projections over the UK.[2]

While some studies have examined the impact of climate change on global or regional solar irradiance, there is no published research that details the projected changes in surface solar radiation on a local or regional scale over South America. The present study aims to fill this knowledge gap, by using a downscaled regional climate model forced by 3 different global climate models to assess the impact of climate change on solar radiation resources over Brazil.

Furthermore, this paper investigates regional projections of wind power and solar radiation concurrently under the same downscaled regional climate models and the same Representative Concentration Pathway (RCP). To our knowledge there are no studies that examine climate change impacts on both these types of renewable energy resources in the South American region. The majority of electricity in South America is generated from renewable energy, for example more than 80% of Brazil's electricity is generated from renewable sources [14]. Yet to date there are only a handful of studies that examine the impact of climate change on renewable energy resources in the region. Moreover, the studies that do exist tend to focus on hydrological projections. There are only 3 previous studies that project *average* wind speeds in the Brazilian region, however, these studies were limited to only 1 climate model with relatively coarse temporal or spatial resolutions. Given that by 2026 the penetration of installed wind and solar power in Brazil's electricity matrix will increase to approximately 18% [15], this study begins to fill the knowledge gaps and is an important step to better enable renewable energy resource planning in the region.

1.2. Wind and solar energy in Brazil

The Brazilian Ministry of Mines and Energy estimate that by 2026, the total installed capacity of solar PV and wind power in Brazil will reach approximately 10,000 MW and 28,000 MW, respectively [15]. Moreover, the large majority of Brazil's utility scale PV and wind power capacity is being installed in the NE region. This is due to the prevalence of excellent wind and solar resources in the NE of Brazil [16,17], as can be observed in Figs. 1 and 2. Therefore, this study will focus on analysing the projected

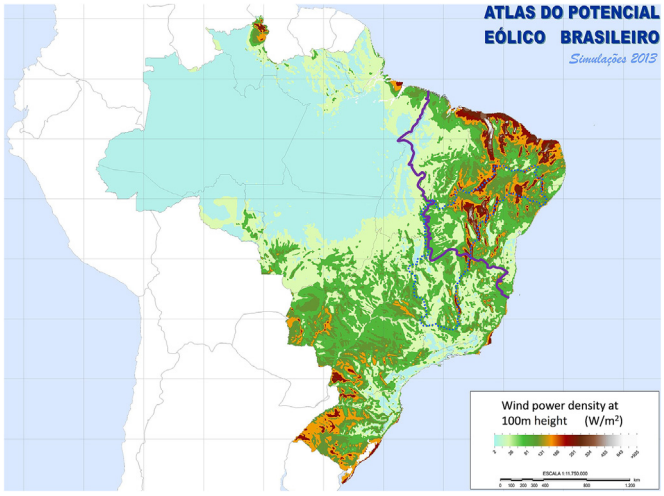

Fig. 1. Wind power density in Brazil at a height above ground level (AGL) of 100 m (which is a typical hub height of modern onshore wind turbines). Source: CEPEL [18]. Note, the Brazilian NE region boundary is shown with a purple line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[1] There is one previous study that projects future wind power density over Brazil [22] which actually used 6 h time intervals with a 40 km horizontal resolution. However, that study used downscaled data from the older HADCM3 global climate model developed in the year 2000.

[2] Specifically, Burnett et al. [13] concluded that average solar energy resources over the UK, under a high emissions scenario, are projected to increase by 4.4% by the 2080s. The increase would be more profound in the south, while solar irradiation could marginally decline in the northwest.

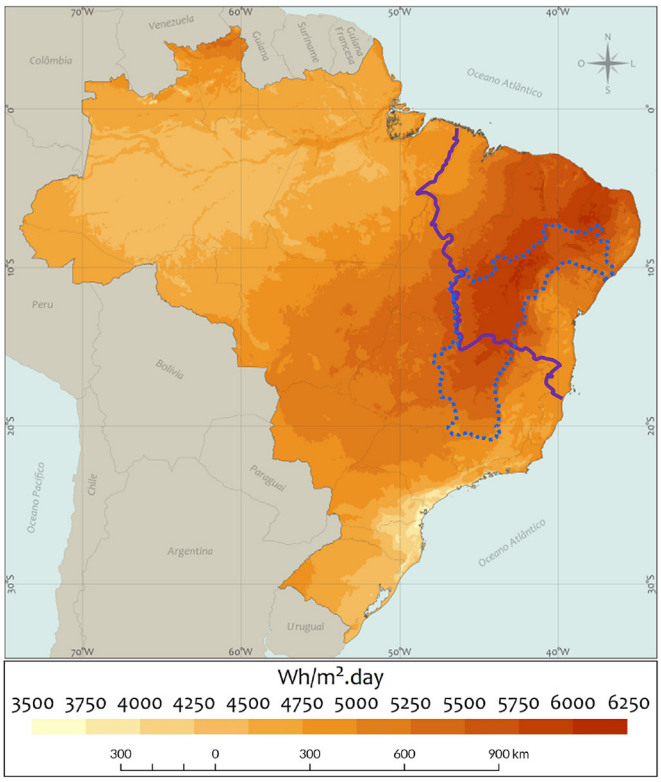

Fig. 2. The annual average daily global horizontal irradiance in Brazil. Source: Pereira et al. [19]. Note, the Brazilian NE region boundary is shown with a purple line while the São Francisco basin area is outlined with a blue dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

changes in renewable energy resources in the NE region.

The technical potential of onshore wind energy in Brazil could be more than 500 GW [20] and by 2020, almost 16 GW of wind power capacity is expected to be installed in the NE region [16]. According to Lucena et al. [21]; by 2070, as a result of increased average wind speeds projected for the North and Northeast regions of Brazil, wind power potential could more than double the 2001 reference baseline potential, and by 2100 it could more than triple the reference baseline. On the other hand, Pereira et al. [22] projected more conservative increases in wind power density of 15–100% across the NE region by the end of the 21st century, but a decrease of up to 15% in wind power density along the coast of Bahia. Both these climate studies relied upon a single climate model. That is, they used downscaled data forced by the HadCM3 global climate model, which was developed for the IPCC Third Assessment Report in 2001.

A more recent study by Ruffato-Ferreira et al. [6] found that for both the RCP4.5 and RCP8.5 emission scenarios, a significant increase in wind speeds is projected for the North, Northeast, Southeast and South regions of Brazil, especially in summer and autumn.[3] However, that study also only used one climate model (the HADGEM2/Eta model).

A statistical analysis of historical wind speed data by Pes et al. [8] found that the frequency of maximum extreme wind speeds, measured on an hourly bases, tended to increase between 1947 and 2014 in most regions of Brazil with the exception of the South region, nevertheless, there were no occurrences of extreme winds over 25 m/s (which is the cut-out speed of large wind turbines).[4]

The total technical potential of centralized solar PV energy in Brazil could be more than 28,500 GW [23]. Currently in Brazil there are approximately 1300 MW of large-scale PV systems already connected to the electricity grid and an additional 2750 MW are under construction or have been contracted for construction [24] and CCEE, 2018. The large majority of these utility scale solar PV projects in Brazil are located in the NE region due to the excellent average daily solar irradiation levels in the semiarid interior of the region. In Fig. 2 the annual average daily global horizontal irradiance is shown for Brazil.

At some locations in the states of Bahia and Paraíba the average daily global irradiance on an inclined plane is in excess of 6 kWh/m^2 and the majority of the middle São Francisco basin area and the western areas of Paraíba and Rio Grande do Norte have an average daily global irradiance in excess of 5.75 kWh/m^2 [19]. Furthermore, with the exception of the South region, all regions of Brazil showed a tendency of increasing solar irradiation from 2005 to 2015, however, due to the relatively short period of the observational data, it cannot be concluded that these changes are due to climate change [19]. Nevertheless, it will be shown that the decline in rainfall projected for the NE, North and Southeast regions over the coming decades could also cause an increase in these regions' average surface solar radiation levels.

1.3. Hydroelectricity in the Northeast region and model uncertainties

Hydrological projections specifically for Brazil's semiarid Northeast (NE) and São Francisco River basin, which are experiencing their worst drought in history [25,26], indicate that the water balance and agricultural production will continue to deteriorate in the coming decades [27–29]. Based on IPCC climate models with high emissions scenarios and historical rainfall trends, average rainfall over the São Francisco basin is projected to continue to decline in the coming decades and this could result in a reduction of approximately 60% in the NE's annual average streamflow and hydroelectric generation compared to baseline data from 1961 to 1990 [3,28,30]. According to Neto et al. [28] streamflows in the Tocantins, Xingu, Parnaíba, Madeira, Tapajós and Maranhão basins are also projected to decline substantially as a result of climate change.

It is worth noting that climate models are subject to cumulative uncertainties and this is especially true for regional scale long-term hydrological projections. Some models can exhibit large biases when compared to observed data and the projections from different models can vary significantly. Nevertheless, most models tend to agree in the overall trend direction of a climate variable (e.g. precipitation) in a particular region.

2. Methodology

Downscaled climate change projection data from 3 different CMIP5 global climate models was obtained from CPTEC-INPE (Centro de Previsão de Tempo e Estudos Climáticos/Weather Forecasting and Climate Studies Centre - Instituto Nacional de Pesquisas Espaciais/National Institute for Space Research) for the

[3] The study also found that the São Francisco, Amazon, Tocantins-Araguaia, and the North and Northeast Atlantic basins are projected to experience a declining water balance under both emissions scenarios. Moreover, the São Francisco is the most vulnerable basin in the country to water scarcity [6].

[4] Similar to Pes et al. [8]; Troccoli et al. [9] found that average wind speed in Australia between 1975 and 2006 increased on average by 0.9% per year considering 14 wind stations with measurements at 10 m AGL.

Brazilian territory. The 3 global climate models are the Hadley Centre Global Environment Model version 2 - Earth System (HADGEM2-ES) developed in the UK, the Model for Interdisciplinary Research on Climate version 5 (MIROC5) developed in Japan, and the Second Generation Canadian Earth System Model (CANESM2). The downscaled projections at higher resolution were carried out by CPTEC-INPE using a South American regional climate model (RCM) known as the Eta Model [31–33]. The output data (generated by CPTEC-INPE) from the 3 downscaled models known as HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta is available on the PROJETA Platform [34]. For each of the 3 models there are projections from 2006 until 2100 considering the RCP8.5 (high emissions) scenario and the RCP4.5 (low emissions) scenario. Hindcast data from each model for the historical period from 1961 to 2005 is also available.

The downscaled projection data used in this study has a 20 km spatial resolution and monthly and 3-h temporal resolutions. Projections of surface incident shortwave (solar) radiation (ISR), wind speeds at a height of 100 m (W100), and average temperature (TP2M) data with the RCP8.5 (high emissions) scenario will be analysed. Analysis will focus on the model projections for solar and wind energy resources in the NE region considering the 2021–2050 and 2070–2099 climate periods in comparison to the 1961–1990 baseline period.

2.1. Solar, wind and temperature changes

Maps showing the percentage changes across Brazil of wind speed, surface solar radiation and temperature will be generated. Furthermore, temperature, solar radiation and wind speed projections from the HADGEM2-ES/Eta model at a few individual locations are compared to historical observations. The observational data was sources from BDMEP [35] and comes from weather stations located in the states of Maranhão, Rio Grande do Sul and Bahia. Observed wind speed data sourced from BDMEP was measured at a height of 10 m above ground level (AGL). However, in the lower troposphere wind speeds typically increase with height, because winds close to the earth's surface are slowed by ground surface friction [36]. Therefore, in order to properly compare observed wind speeds with modelled data at 100 m AGL, the observed average annual wind speeds at 10 m AGL are extrapolated to 100 m AGL using the wind profile power law. The power law equation is expressed as:

$$v/v_0 = (H/H_0)^{\alpha}; \quad (1)$$

Where v is *wind speed* (m/s) at *height* H (in this case 100 m) and v_o is a known speed at height H_o (in this case 10 m). α is known as the Hellmann exponent or (surface) friction coefficient and is a function of the local topography [36]. In this study an α of 0.20 was assumed, which corresponds to a terrain type of crops, hedges and/or shrubs.

Additionally, the changes in solar radiation and wind speeds will be estimated for specific locations where solar and wind power generation infrastructure has or will be developed, respectively, in order to quantify how generation from these renewable resources could change in terms of yield and reliability. The statistical

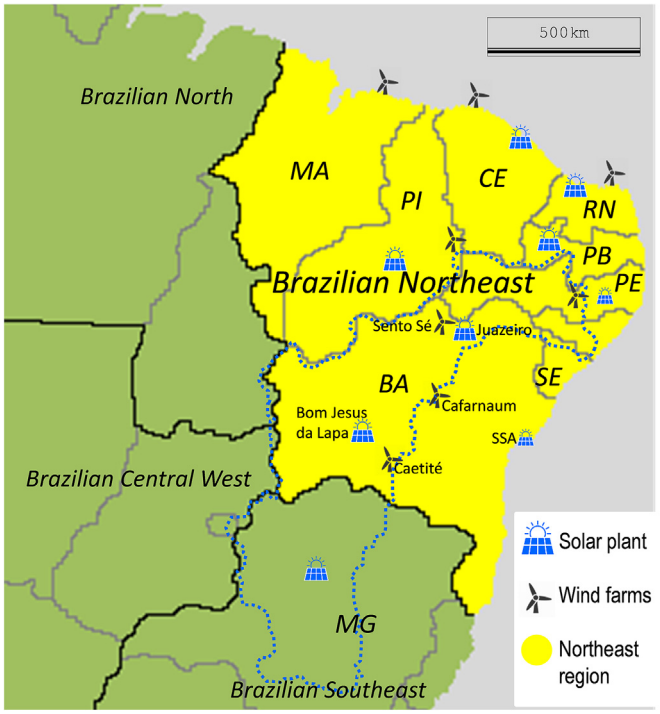

Fig. 3. Location of major wind farm centres and solar PV installations. Additionally, the São Francisco basin area is outlined with a blue dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
The planned capacity and home state of major wind farm centres (LHS) and solar PV installations (RHS). Key: BA – Bahia; CE – Ceará; MA – Maranhão; PB – Paraíba; PE – Pernambuco; PI – Piauí; RN – Rio Grande do Norte; SE – Sergipe; MG – Minas Gerais; SP – São Paulo; RS – Rio Grande do Sul. Note, installations in RS and SP do not appear on the map in Fig. 3 below.

State	Wind farm locations	Wind capacity (MW)
BA (Sth)	Caetité/Guanambi	1635
BA	Cafarnaum	863
BA (Nth)	Sento Sé	1150
CE	Acaraú/Itarema	856
MA	Barreirinhas	316
PE	Caetés	612
PI	Marcolândia	1639
RN	Parazinho/João Câmara	2349
RS	Santa Vitória do Palmar/Chuí	869

State	Solar farm locations	Solar capacity (MW)
BA (Sth)	Bom Jesus Lapa/Tabocas Brejo Velho	309
BA	Salvador (SSA)	0.405
BA (Nth)	Juazeiro	122
CE	Aquiraz	84
PE	Agrestina	30
PI	Ribeira do Piauí/João Costa - PI	270
PB	Coremas/Malta	111
RN	Areia Branca	86
MG	Pirapora - MG	321
SP	Guaimbê - SP	150

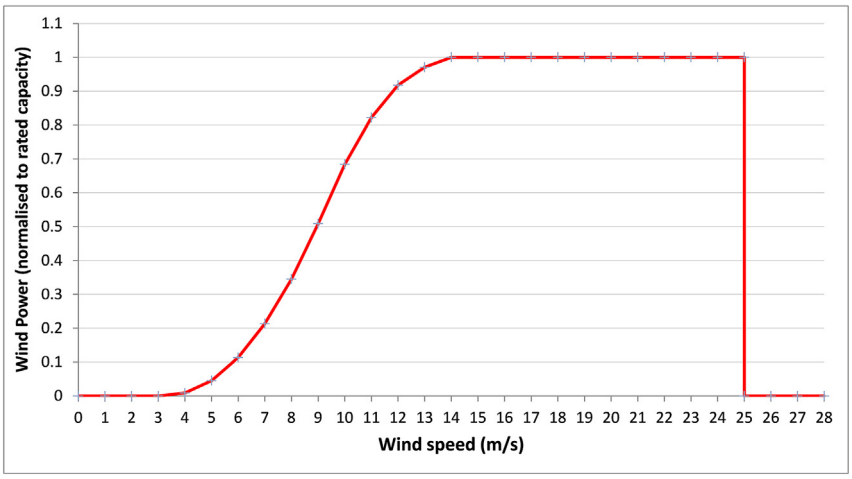

Fig. 4. Normalised power curve for a typical wind turbine in Brazil.

significance of changes in wind speed and solar radiation from the baseline climate period to future periods are verified with the Student's paired *t*-test with a two-tailed distribution.[5]

The location and planned capacity of the major wind farm centres and utility scale solar PV installations in Brazil are shown in Table 1 and Fig. 3. For each of these locations the respective wind speed and solar radiation projections using the HADGEM2-ES/Eta RCP8.5 scenario will be analysed. (The HADGEM2-ES/Eta model was chosen as the default model because, in general, projected changes from this model were close to the median of all 3 models). The percentage change in the resource magnitude (wind power and solar radiation) compared to the baseline data is then calculated. Specifically, the percentage changes in wind power density by 2070–2099 compared to the baseline period are estimated from the changes in wind speeds using the following equation:

$$\textit{Wind Power Density}(WPD) = {}^{1}\!/_{2} \cdot \rho \cdot V^{3}; \quad (2)$$

Where ρ is the density of air and V is the velocity or wind speed.

The Caetité/Guanambi and Parazinho/João Câmara municipalities, which are major wind farm areas in the NE, as well as the municipalities of Barreirinhas and Santa Vitória do Palmar/Chuí were chosen for further analysis. At these locations, as well as using the HADGEM2-ES/Eta model, the wind speeds and changes in wind power density are also projected under the MIROC5/Eta RCP8.5 and CANESM2/Eta RCP8.5 scenarios. Additionally, the Weibull shape factor, *k*, of the wind speed distribution is estimated for the 3 different 30-year climate periods at each of the 4 locations using the Likelihood function. Furthermore, the wind power generation at these locations, using wind speed data with a temporal resolution of 3 h, is calculated according to a standard normalised power curve for typical wind turbines used in Brazil (see Fig. 4). This enables a more accurate estimation of the average wind power capacity factor for each 30-year climate period. In turn, the change in wind power generation (average capacity factor) by 2021–2050 and 2070–2099 relative to the baseline period can be calculated. Additionally, the standard deviation of the wind power capacity factor for each climate period is also calculated.

The municipalities of Pirapora in Minas Gerais and Guaimbê in the state of São Paulo, which are important locations for large-scale solar PV installations, were chosen for further analysis. At these locations, as well as using the HADGEM2-ES/Eta model, solar radiation was also projected under the MIROC5/Eta RCP8.5 and CANESM2/Eta RCP8.5 scenarios. Furthermore, projections of solar radiation at Pirapora and wind speed at Caetité were also conducted using the HADGEM2-ES/Eta RCP4.5 (low emissions) scenario.

3. Results

3.1. Solar energy

The changes in average temperature and percentage change in surface solar radiation under the RCP 8.5 scenario projected for 2070–2099 compared to the baseline period of 1961–1990 can be observed in Fig. 5. It should be noted, that there are no existing or planned large-scale solar power plants in the North region of Brazil because the solar resources are very low compared to the rest of the country. Therefore, despite the larger percentage increase in solar radiation projected for some areas of the North region, the solar resources in that region will still remain relatively low in comparison to the resources in the NE region.

It can be observed in Fig. 5 (RHS) that by the 2080s, solar radiation is projected to increase across most of Brazil compared to the 1970s. This is in stark contrast to some other regions in the world, such as India and Northwest China, which could see significant declines in solar radiation [11]. Nevertheless, while temperature is expected to increase across all of Brazil, solar radiation in the far south of the country is projected to decline. This can also be observed in Fig. 6, which shows temperature and solar radiation projections compared to historical observations from 1961 to 2018 at Imperatriz in the state of Maranhão and at Santa Vitoria do Palmar in the state of Rio Grande do Sul. (Imperatriz is located on the most westerly edge of the NE region and Santa Vitoria do Palmar is located in the extreme south of Brazil). The top graph in Fig. 6 shows that since 1961–1965, the average temperature measured at Imperatriz has increased by approximately 2 °C and under the RCP8.5 high emission scenario it is projected to increase an additional 6 °C by 2100.

Additionally, in Fig. 6, it can be observed that projected solar radiation (ISR) data and in particular historical insolation data show an increasing trend at Imperatriz while a slight decreasing trend of observed and modelled data is present at Santa Vitoria do Palmar.

However, it should be noted that projections of absolute solar

[5] Before applying the Student's t-test, it was verified that the data used in the test follows a normal distribution, as this is the primary requirement for applying the Student's t-test.

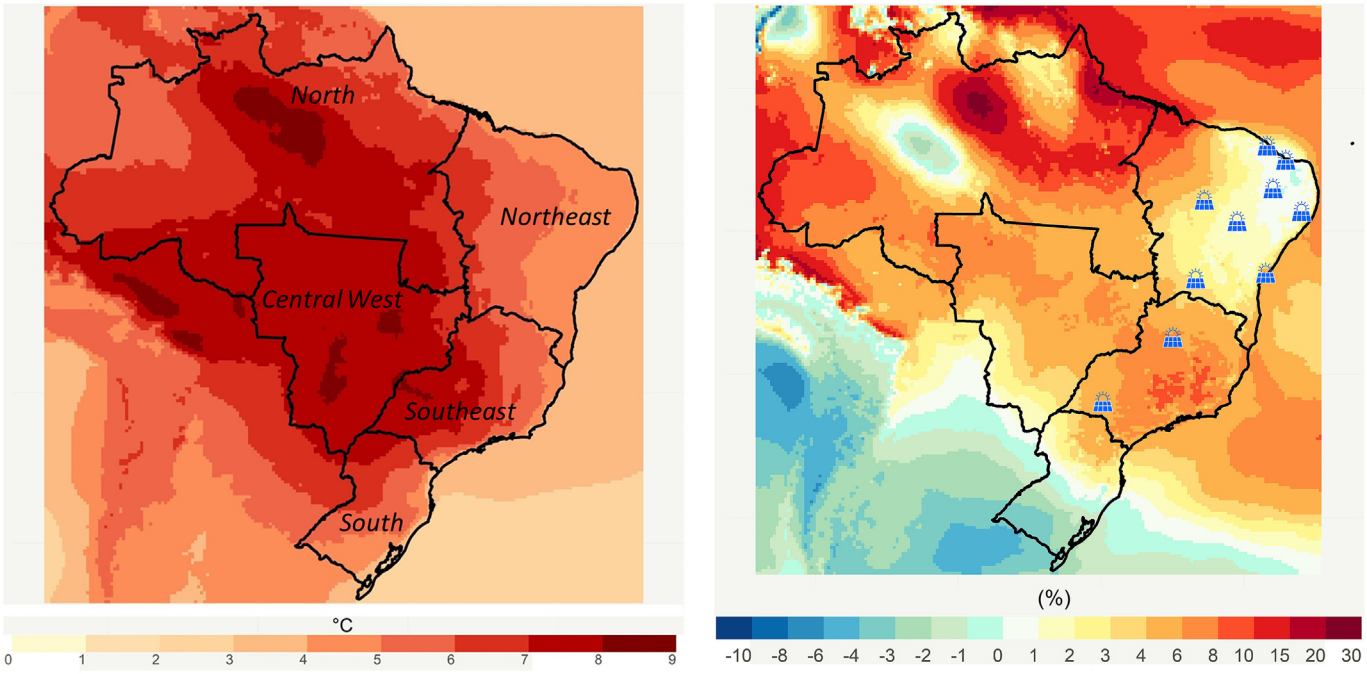

Fig. 5. Climate projections under the HADGEM2-ES/Eta RCP8.5 scenario. LHS: Changes in average temperature (°C) projected for 2070–2099 compared to the 1961–1990 baseline period in the different regions of Brazil. RHS: Percentage change in surface solar radiation projected for 2070–2099 compared to the baseline period of 1961–1990 with the location of large-scale solar power plants shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

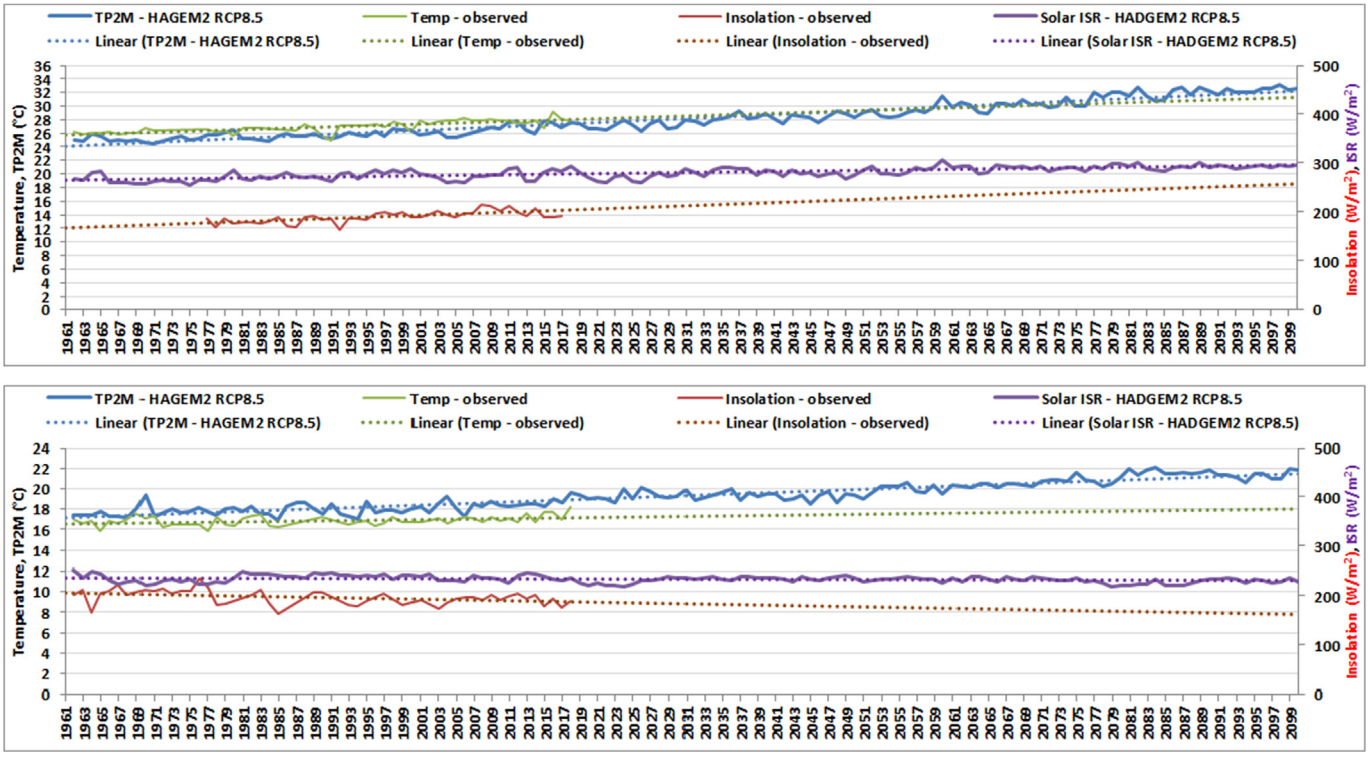
TP2M - HAGEM2 RCP8.5
Temp - observed
Insolation - observed
Solar ISR - HADGEM2 RCP8.5
Linear (TP2M - HAGEM2 RCP8.5)
Linear (Temp - observed)
Linear (Insolation - observed)
Linear (Solar ISR - HADGEM2 RCP8.5)
Temperature, TP2M (°C)
Insolation (W/m²), ISR (W/m²)

Fig. 6. Temperature–TP2M (°C) and surface solar radiation–ISR (W/m^2) projections (using the HADGEM2-ES/Eta RCP8.5 scenario) compared to historical observations of temperature (°C) and insolation (hours/month) at Imperatriz in the state of Maranhão (top) and at Santa Vitoria do Palmar in the state of Rio Grande do Sul (bottom).

radiation (in W/m^2) at both these locations, as well as all other locations analysed in Table 2, demonstrated a positive bias of around 20–45% compared to observed solar radiation data from the INMET (Instituto Nacional de Meteorologia/Brazilian National institute of Meteorology). That is, the average biases at Imperatriz and Santa Vitoria do Palmar were 84 W/m^2 and 39 W/m^2, respectively. Similarly, the Root Mean Square Error (RMSE), between observed and projected solar radiation data at these locations was

Table 2
Changes in solar radiation at various solar PV plants. Unless otherwise stated, the HADGEM2-ES/Eta model was used with the RCP8.5 scenario. Statistically insignificant changes (where the p-value was greater than 0.05) are shown in italics. Note, the *Percentage change* in average solar radiation is relative to the 1961–1990 baseline period.

State	Solar farm locations	1961–1990	2021–2050		2070–2099	
		Avg solar radiation (W/m^2)	Avg solar radiation (W/m^2)	Percentage change	Avg solar radiation (W/m^2)	Percentage change
BA (Sth)	Bom Jesus Lapa/Tabocas Brejo Velho	303	309	2.0%	312	2.8%
BA	Salvador (SSA)	249	257	3.2%	261	4.7%
BA (Nth)	Juazeiro	312	315	1.1%	317	1.6%
CE	Aquiraz	281	281	*0.1%*	284	*1.0%*
PE	Agrestina	303	303	*0.1%*	304	*0.5%*
PI	Ribeira do Piauí/João Costa - PI	300	305	1.9%	309	3.2%
PB	Coremas/Malta	310	312	*0.5%*	312	*0.5%*
RN	Areia Branca	301	301	*0.2%*	302	*0.3%*
All	**(Entire NE region polygon)**	284	288	*1.7%*	294	3.6%
MG	Pirapora (HADGEM2-ES RCP8.5)	279	292	4.3%	297	6.3%
MG	Pirapora (HADGEM2-ES RCP4.5)	279	284	*1.5%*	286	2.5%
MG	Pirapora (MIROC5 RCP8.5)	257	260	*0.8%*	267	3.8%
MG	Pirapora (CANESM2 RCP8.5)	273	287	**5.0%**	304	**11.6%**
SP	Guaimbê (HADGEM2-ES RCP8.5)	276	280	1.6%	279	1.1%
SP	Guaimbê (MIROC5 RCP8.5)	265	253	**−4.2%**	255	**−3.8%**
SP	Guaimbê (CANESM2 RCP8.5)	261	264	1.5%	272	4.6%

estimated to be 85 W/m^2 and 43 W/m^2, respectively. Therefore, this implies that most of the hindcast error was actually due to the positive biases."

It should be noted that models of global shortwave solar radiation are known to exhibit positive biases as reported by Zhang et al. [37] who found that reanalysis data products overestimated measured solar radiation by 11–50 W/m^2. Nevertheless, it is assumed that such biases observed in climate models remain reasonably constant regardless of the climate period and therefore, should not significantly influence the projected long term changes in climate variables such as average solar radiation and wind speeds [38].

Considering the specific solar farm locations shown in Table 1, the changes in solar radiation projected for 2021–2050 and 2070–2099 compared to the baseline period of 1961–1990 can be observed in Table 2.[6]

From Table 2, it can be observed that only one location (Guaimbê in the state of São Paulo) under the MIROC5 model showed a decrease in solar radiation. At all other locations a slight increase in solar radiation is projected and the highest increase is projected for Pirapora in Minas Gerais. However, the projected increases in solar radiation at the Aquiraz, Agrestina, Coremas/Malta and Areia Branca solar farm locations in the states of Ceará, Paraíba, Pernambuco and Rio Grande do Norte are statistically insignificant. Projected changes in solar radiation by 2070–2099 at all other locations were found to be statistically significant."

3.2. Wind energy

The percentage change in wind speeds at a height of 100 m above ground level (AGL) across Brazil under the RCP 8.5 scenario projected for 2070–2099 compared to the baseline period of 1961–1990 can be observed in Fig. 7. It should be noted, that there are no existing or planned large-scale wind farms in the North region of Brazil because average wind speeds in that region are extremely low compared to the rest of the country. Therefore, despite the very large percentage increases in average wind speeds projected for most of the North region, the wind resources in the region will still remain relatively low compared to the excellent wind resources in the NE and South regions of Brazil.

In Fig. 7 it can be observed that wind speeds are projected to increase across most of Brazil which is consistent with the findings of Ruffato-Ferreira et al. [6]. However, a slight decline in wind speeds could occur in the small NE states of Rio Grande do Norte and Paraíba, especially considering the CANESM2/Eta model. Fig. 8 shows wind speed projections compared to historical wind speed observations extrapolated to 100 m AGL from 1961 to 2018 at Caetité in the state of Bahia and at Santa Vitoria do Palmar in the state of Rio Grande do Sul. Observed average annual wind speeds measured at 10 m AGL were extrapolated to a height of 100 m AGL using the wind profile power law (see equation (1)).

It should be noted that the friction coefficient, α, actually varies at a specific location and depends on several factors including height, time of the day, season and various meteorological conditions [36]. Therefore, using the wind profile power law only allows for an *estimation* of the average annual wind speed at a hub height of 100 m. Furthermore, the modelled wind speed data is subject to biases. It can be observed in Fig. 8 that the modelled data has an average positive bias of approximately 20% in excess of the extrapolated wind speed observations. Specifically, the average biases between extrapolated observations and projected wind speed at Caetité and Santa Vitoria do Palmar were estimated to be 1.3 m/s and 1.1 m/s, respectively. The RMSE results were only marginally larger than the average biases and, therefore, this implies that the large majority of the hindcast error was actually due to the positive bias. Consequently, the bias appears to remain reasonably constant throughout the hindcast period which indicates that the climate model is useful in projecting long term changes in average wind speeds.

It can be observed that both projected wind speed (W100) and historical wind speed data show an increasing trend at Santa Vitoria do Palmar. However, while the projected wind speed data at Caetité shows an increasing trend, observed wind speeds from 1961 to 2013 show a slight decreasing trend. It should be noted that there are several years without observational readings between 1981 and 1996. Furthermore, observed wind speeds at Caetité are taken from

[6] It should be noted that PV efficiency is negatively affected by increasing ambient temperature. For example, a projected increase of 6 °C would cause a reduction in PV output power of approximately 1.5%, considering today's commercially available PV panels. However, PV efficiencies are continually improving with advances in technology and it is almost impossible to estimate with any certainty the exact efficiency improvements of future PV technologies. Therefore, the scope of the present analysis is solely focussed on the impact of climate change on solar irradiation resources.

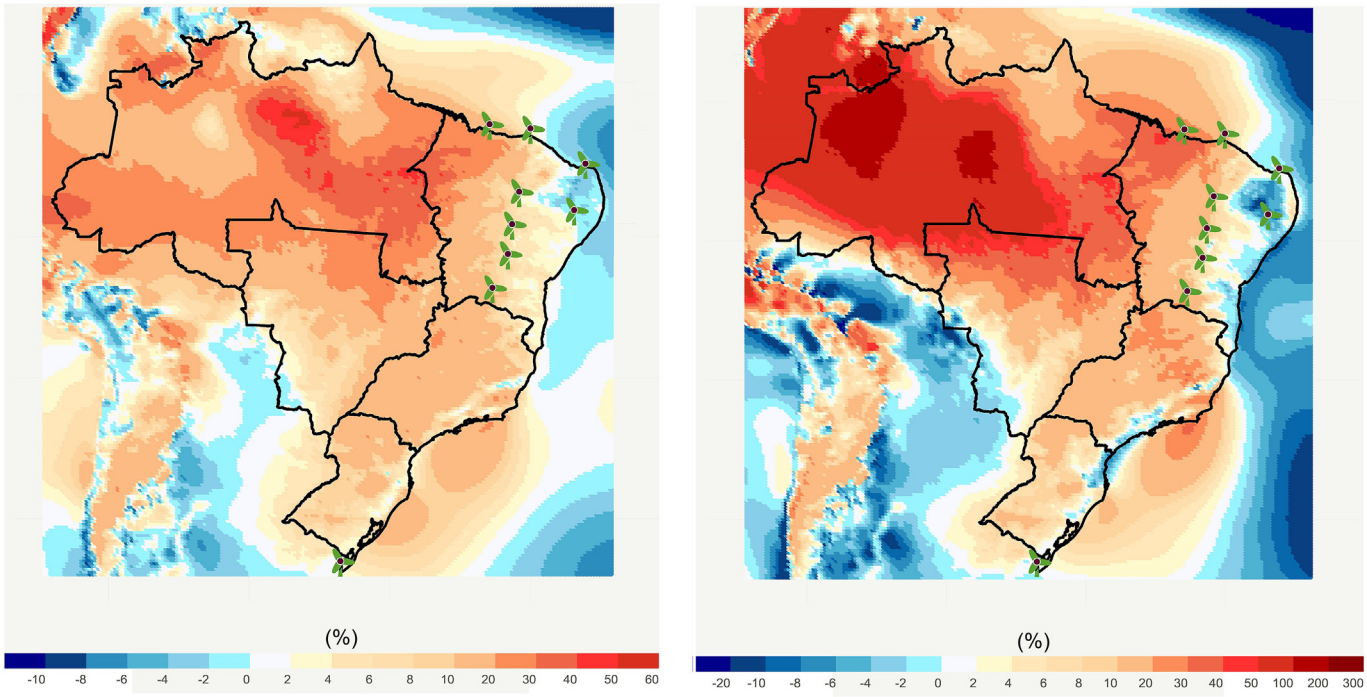

Fig. 7. Percentage change in wind speeds at 100 m AGL projected for 2070–2099 under the RCP8.5 scenario compared to the baseline period of 1961–1990. LHS: Using the HADGEM2-ES/Eta model. RHS: Using the CANESM2/Eta model. (Major wind farm centres in Brazil are shown in green and black). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

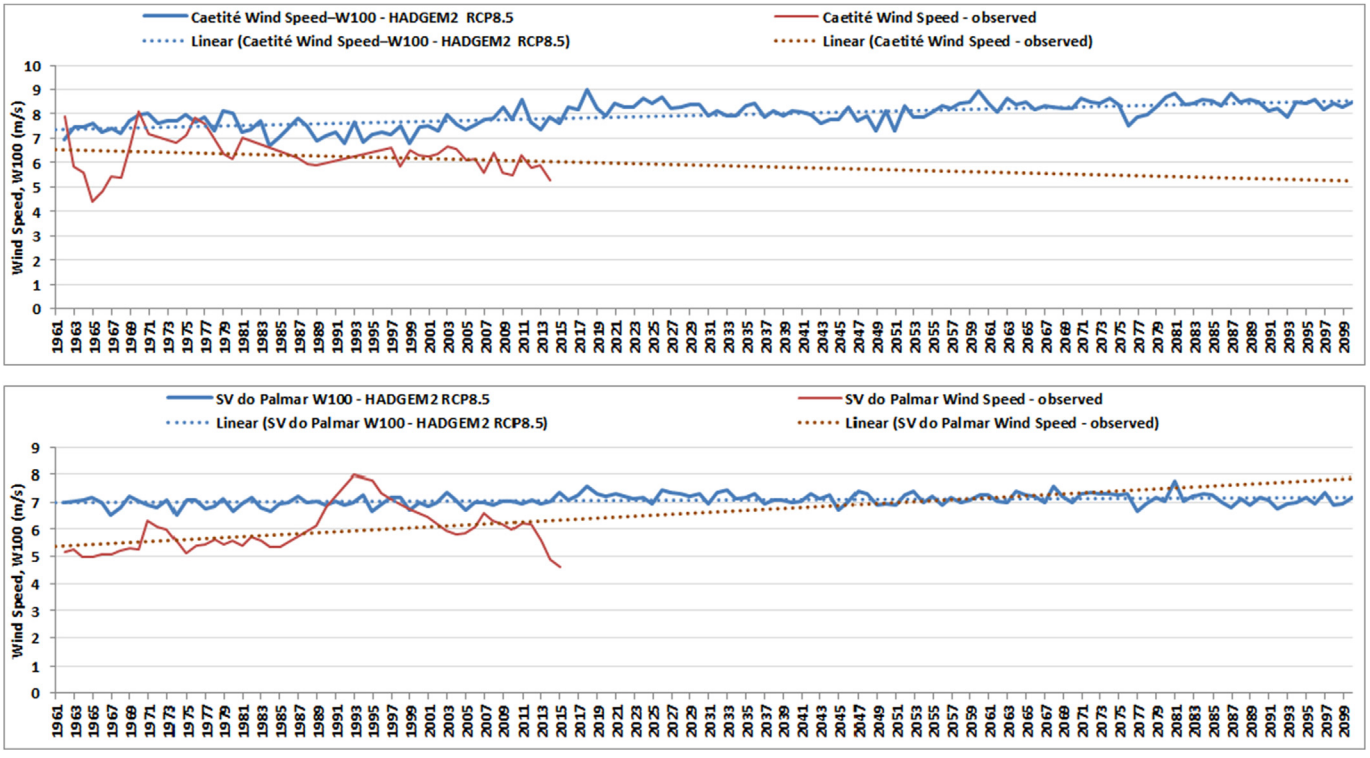
Caetité Wind Speed–W100 - HADGEM2 RCP8.5
Caetité Wind Speed - observed
Linear (Caetité Wind Speed–W100 - HADGEM2 RCP8.5)
Linear (Caetité Wind Speed - observed)
Wind Speed, W100 (m/s)
SV do Palmar W100 - HADGEM2 RCP8.5
SV do Palmar Wind Speed - observed
Linear (SV do Palmar W100 - HADGEM2 RCP8.5)
Linear (SV do Palmar Wind Speed - observed)
Wind Speed, W100 (m/s)

Fig. 8. Wind speed–W100 projections (at 100 m AGL using the HADGEM2-ES/Eta RCP8.5 scenario) compared to historical wind speed observations (extrapolated to 100 m AGL) at Caetité in the state of Bahia (top) and at Santa Vitoria do Palmar in the state of Rio Grande do Sul (bottom).

an anemometer at 10 m above the ground in an urban area which over the years has grown in size. Therefore, it is likely that urban development in Caetité has distorted the trend in observed wind speed data and could be the reason for the decline in measured wind speeds during the observational period. This type of problem with observed long-term wind speed data was also highlighted by

Troccoli et al. [9].

Considering the specific wind farm locations shown in Table 1, the percentage change in wind speeds at 100 m AGL projected for 2021–2050 and 2070–2099 compared to the 1961–1990 baseline period can be observed in Table 3.

It can be observed that only one location (Parazinho/João Câmara in the state of Rio Grande do Norte) under both the HADGEM2-ES and MIROC5 models showed a decrease in average wind speed. However, the projected change in wind speed at that same location (Parazinho/João Câmara) using the CANESM2 model is insignificant. At all other locations an increase in wind speeds is projected considering the HADGEM2-ES and CANESM2 models. Though, the projected increase in wind speeds at wind farm locations in Caetés, Pernambuco under the HADGEM2-ES model becomes statistically insignificant by 2070–2099. All other projected changes in wind speed by 2070–2099 were found to be statistically significant. The highest increase is projected for Barreirinhas in Maranhão, however, against both observed trends and increasing wind speed projections from the other models, the MIROC5 model projected a decrease in wind speeds at Barreirinhas and also at Santa Vitória do Palmar in Rio Grande do Sul. Therefore, it appears that the MIROC5/Eta model is the least reliable of the 3 models at simulating observed wind speed trends in the region. The wind power density at Barreirinhas considering the HADGEM2-ES/Eta RCP8.5 and CANESM2 models is projected to increase by 42% and 72%, respectively. These results suggest that the Lucena et al. [21] study substantially overestimated increases in wind power potential over the NE of Brazil projected for 2070–2100. Furthermore, considering the installed capacities of the various wind farm centres shown in Table 1, the overall wind power output from these wind farms is projected to increase only 12% by the 2080s under the HADGEM2-ES model.

The probability distribution of wind speeds typically varies from month to month and even several times during a 24-h day. For example, wind speeds in Bahia are typically higher at night and early morning than during the middle of the afternoon [16,17]. As a result, it is important to consider the impact of these variations in wind speed on wind power generation. This is because wind power generation is not linearly proportional to wind speed as can be observed in Fig. 4. In fact, once the wind speed climbs above the rated wind speed of a turbine (typically 13–14 m/s) there is no additional wind power generation beyond the rated capacity of the turbine.

Therefore, wind speed simulation data with a temporal resolution of 3 h was obtained using the 3 models (HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta) considering the RCP8.5 scenario at

Table 3
The projected average *Wind speed* and *Weibull shape factork* at various wind farm locations. Additionally, the *Percentage change in wind speeds* are estimated relative to the 1961 -1990 baseline period. The last column shows the *Percentage change in wind power density* projected for 2070 -2099 relative to the 1961 -1990 baseline period. Statistically insignificant changes (where the p-value was greater than 0.05) are shown in italics.

State	Wind farm locations (Model)	1961–1990		2021–2050			2070–2099			
		Wind speed (m/s)	Weibull shape factor k	Wind speed (m/s)	Weibull shape factor k	Percentage change in wind speed	Wind speed (m/s)	Weibull shape factor k	Percentage change in wind speed	Percentage change in wind power density
BA (Sth)	Caetité/Guanambi (HADGEM2 RCP8.5)	7.51	(2.68)	8.07	(2.90)	7.5%	8.39	(3.16)	11.7%	36.3%
BA (Sth)	Caetité/Guanambi (HADGEM2 RCP4.5)	7.51		7.85		4.5%	7.92		5.5%	17.0%
BA (Sth)	Caetité/Guanambi (MIROC5 RCP8.5)	6.98	(2.50)	7.32	(2.60)	4.8%	7.39	(2.59)	5.8%	15.3%
BA (Sth)	Caetité/Guanambi (CANESM2 RCP8.5)	7.21	(2.50)	7.84	(2.75)	8.7%	8.56	(3.16)	**18.8%**	**49.0%**
BA	Cafarnaum (HADGEM2 RCP8.5)	7.53		7.87		4.4%	8.04		6.8%	19.6%
BA (Nth)	Sento Sé (HADGEM2 RCP8.5)	6.22		6.50		4.5%	6.66		7.2%	20.3%
CE	Acaraú/Itarema (HADGEM2 RCP8.5)	4.91		5.08		3.3%	5.25		6.8%	15.4%
MA	Barreirinhas (HADGEM2 RCP8.5)	6.12	(2.60)	6.61	(2.79)	8.0%	7.17	(3.34)	**17.1%**	**41.7%**
MA	Barreirinhas (MIROC5 RCP8.5)	6.05	(1.84)	5.69	(1.84)	−5.9%	5.76	(1.86)	**−4.7%**	**−13.3%**
MA	Barreirinhas (CANESM2 RCP8.5)	6.96	(2.56)	7.27	(3.07)	4.5%	9.24	**(7.94)**	**32.9%**	**71.7%**
PE	Caetés (HADGEM2 RCP8.5)	6.85		6.95		1.4%	6.86		*0.2%*	*0.6%*
PI	Marcolândia (HADGEM2 RCP8.5)	6.72		6.88		2.4%	7.01		4.2%	9.7%
RN	Parazinho/J Câmara (HADGEM2 RCP8.5)	7.49	(3.87)	7.48	(3.99)	*−0.1%*	7.29	(3.75)	**−2.6%**	**−7.0%**
RN	Parazinho/J Câmara (MIROC5 RCP8.5)	8.12	(4.28)	7.87	(4.03)	−3.1%	7.72	(3.87)	**−4.9%**	**−11.5%**
RN	Parazinho/J Câmara (CANESM2 RCP8.5)	8.14	(4.87)	8.21	(5.01)	*0.9%*	8.13	(4.98)	*0.0%*	*−1.5%*
All	**Entire NE region** (HADGEM2 RCP8.5)	5.65		5.91		4.7%	6.18		9.4%	31.1%
RS	S V do Palmar/Chuí (HADGEM2 RCP8.5)	6.95	(2.59)	7.15	(2.61)	2.9%	7.12	(2.65)	2.4%	7.2%
RS	S V do Palmar/Chuí (MIROC5 RCP8.5)	7.39	(2.52)	7.22	(2.49)	−2.3%	7.08	(2.42)	**−4.2%**	**−11.8%**
RS	S V do Palmar/Chuí (CANESM2 RCP8.5)	7.12	(2.64)	7.09	(2.67)	*−0.4%*	7.22	(2.76)	1.4%	1.4%

Table 4
Normalised wind power (capacity factor), its standard deviation and the percentage change in wind power at 4 wind farm locations considering the HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta models under the RCP8.5 scenario. Note, the percentage change in wind power is relative to the 1961-1990 baseline period.

State	Wind farm locations (Model) RCP8.5	1961–1990		2021–2050			2070–2099		
		Wind power capacity factor	(Standard Deviation)	Wind power capacity factor	(Standard Deviation)	Change in wind power	Wind power capacity factor	(Standard Deviation)	Change in wind power
BA (Sth)	Caetité/Guanambi (HADGEM2)	0.385	(0.29)	0.445	(0.31)	15.7%	0.476	(0.31)	**23.9%**
BA (Sth)	Caetité/Guanambi (MIROC5)	0.327	(0.27)	0.364	(0.29)	11.4%	0.374	(0.29)	14.3%
BA (Sth)	Caetité/Guanambi (CANESM2)	0.355	(0.29)	0.419	(0.31)	18.2%	0.498	(0.31)	**40.5%**
MA	Barreirinhas (HADGEM2)	0.223	(0.20)	0.271	(0.23)	21.5%	0.323	(0.23)	**44.8%**
MA	Barreirinhas (MIROC5)	0.269	(0.28)	0.228	(0.25)	−15.2%	0.236	(0.25)	−12.2%
MA	Barreirinhas (CANESM2)	0.331	(0.27)	0.346	(0.26)	4.4%	0.570	(0.17)	**72.0%**
RN	Parazinho/J Câmara (HADGEM2)	0.355	(0.21)	0.350	(0.21)	−1.4%	0.328	(0.21)	−7.7%
RN	Parazinho/J Câmara (MIROC5)	0.432	(0.22)	0.405	(0.22)	−6.2%	0.386	(0.22)	−10.6%
RN	Parazinho/J Câmara (CANESM2)	0.425	(0.21)	0.431	(0.21)	1.5%	0.417	(0.22)	−1.8%
RS	S V do Palmar/Chuí (HADGEM2)	0.304	(0.25)	0.322	(0.26)	6.0%	0.319	(0.25)	4.9%
RS	S V do Palmar/Chuí (MIROC5)	0.349	(0.28)	0.332	(0.27)	−4.9%	0.317	(0.26)	−9.1%
RS	S V do Palmar/Chuí (CANESM2)	0.320	(0.25)	0.316	(0.25)	−1.2%	0.328	(0.25)	2.7%

the following wind farm locations: Caetité/Guanambi, Parazinho/João Câmara, Barreirinhas and Santa Vitória do Palmar/Chuí.

This data enables an estimate of the normalised wind power generation and its standard deviation at each of these 4 locations under each model for the 3 climate periods used in this study (see Table 4). Furthermore, the change in wind power generation (capacity factor) by 2021–2050 and 2070–2099 relative to the 1961–1990 baseline period can also be observed in Table 4.

It can be observed that at one wind farm location (Parazinho/João Câmara in the state of Rio Grande do Norte) all the models projected a small decline in wind power by 2070–2099. However, at the other 3 wind farm locations, at least 2 out of the 3 models agreed that there would be a significant increase in wind power. Moreover, at Caetité/Guanambi and Barreirinhas in the NE region, wind power is projected to increase significantly by 2021–2050 and could increase substantially by 2070–2099.

Additionally, the changes in wind power by 2070–2099 are typically more than double the changes in average wind speed (shown in Table 3), but usually somewhat less than the changes in wind power density (shown in the last column of Table 3).

The wind speed simulation data with a temporal resolution of 3 h was also used to calculate the Weibull shape factor k for the 3 different climate periods at the same 4 wind farm locations. Therefore, the Weibull shape factor k is shown in brackets in Table 3. In general, if an increase in wind speed is projected, then a slight increase in the shape factor k is also projected. However, the results for one site (Barreirinhas) under the CANESM2/Eta climate model stand out, as the shape factor k, estimated to be 2.56 for the 1961–1990 period, is projected to increase to 7.94 by 2070–2099. Therefore, this projection indicates a fundamental change in the wind regime at Barreirinhas in the state of Maranhão and this can be observed in Fig. 9. By 2070–2099 the wind speed distribution at this location is projected to have a very high shape factor k which indicates the predominance of very consistent wind speeds around the mean wind speed. This means that in addition to the high average wind speed projected for Barreirinhas, occurrences of extreme low and high wind speeds, which fall outside the operational range of a typical wind turbine, are very unlikely. Nevertheless, the results from the CANESM2/Eta model for Barreirinhas should be treated with caution as the other 2 climate models did not demonstrate such a fundamental change in the wind regime at the same location.

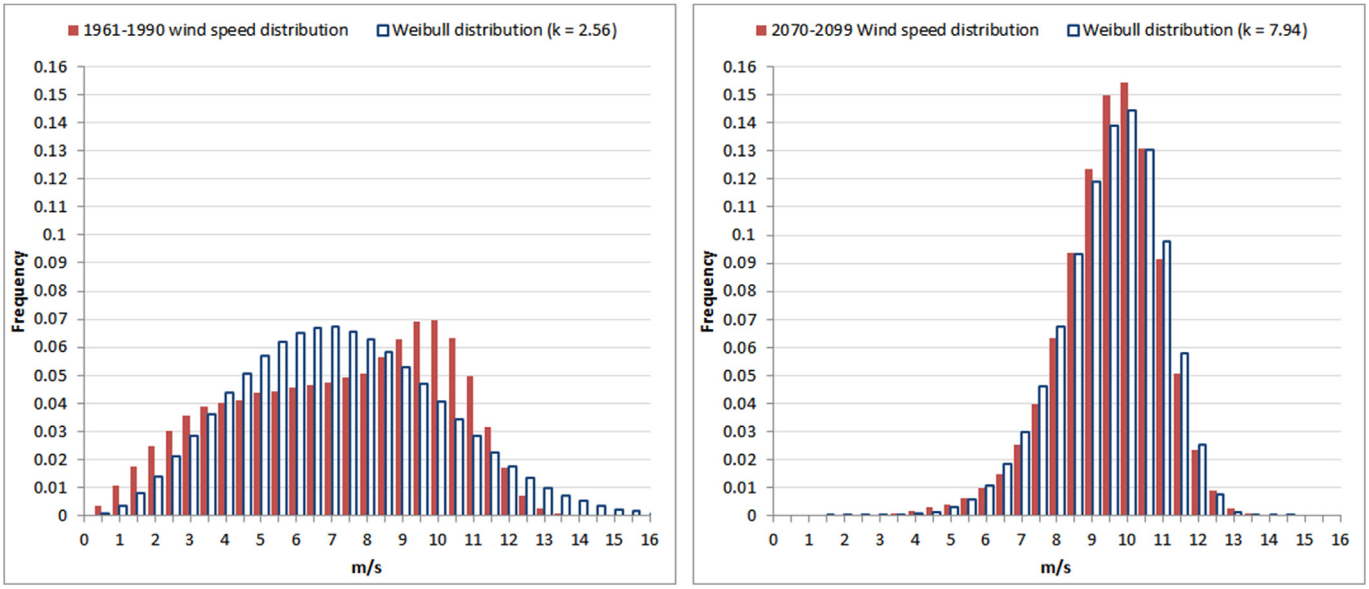

Fig. 9. Wind speed frequency distribution and Weibull approximation at Barreirinhas in the state of Maranhão using the CANESM2/Eta model. LHS: 1961–1990 climate period. RHS: 2070–2099 climate period.

4. Conclusions

Climate change is predicted to cause significantly reduced rainfall and higher temperatures in most regions of Brazil compared to the end of the 20th century. Specifically, de Jong et al. [3] concluded that streamflow in semiarid regions (such as the São Francisco basin) are particularly vulnerable to climate change. Conversely, it was found that by the 2080s, surface solar radiation is projected to increase across most of Brazil and could increase on average by 3.6% across the NE region compared to the 1970s. There was a consensus that solar radiation would increase at all solar farm locations analysed in the NE region, although the increase at some sites could be insignificant. Additionally, the large-scale solar PV installations at Pirapora in the state of Minas Gerais could see an increase in solar radiation of up to 11.6% according to the CANESM2/Eta model. On the other hand, the installations at Guaimbê in the state of São Paulo could see a decline in solar radiation of 3.8% according to the MIROC5/Eta model. Nevertheless, the other 2 models projected a slight increase in solar radiation at the same location.

In general, the CANESM2/Eta model projected the biggest increases in solar radiation and wind speeds by the 2080s across most of Brazil. In comparison, the HADGEM2-ES/Eta model typically showed intermediate increases in solar radiation and wind speeds, while the MIROC5/Eta model demonstrated smaller increases at some locations and slight decreases at other locations. However, the MIROC5/Eta model appeared to be the least reliable model of the three for simulating past climate data in Brazil (such as historical wind data). This result is consistent with the findings of McSweeney et al. [39] who showed that the MIROC global climate models exhibited significant shortcomings in reproducing historical observations.

By the 2080s wind speeds across the majority of the NE region are projected to increase on average by 9.4% compared to the end of the 20th century under the HADGEM2-ES/Eta model. Overall, the results suggest that the projected increases in wind speeds across Brazil are in stark contrast with wind speed projections over other regions in the world such as Europe and Africa where wind speeds are expected to mostly decline or remain the same, respectively. Moreover, at some wind farm locations in the NE states of Bahia and Maranhão wind speeds could increase by up to 19% and 33%, respectively, according to the CANESM2/Eta model. This could see an increase in average wind power density of 49% and 72%, respectively by the 2080s. Due to the efficiency limits of typical wind turbines, this means an increase of 40% and 72%, respectively in average wind power at these 2 locations. However, given the differing results amongst the 3 climate models, this study also demonstrates the large uncertainties and variations between different downscaled climate models, particularly when estimating long-term wind speeds. Additionally, significant biases were found between observed and projected data. While it is assumed that bias errors observed in climate models typically remain constant regardless of the climate period, the results of this study should be treated as preliminary.

In order to more accurately estimate changes in climate variables, more research is required using an ensemble of local climate models that could be bias adjusted according to historical data. In this regard, reliable historical solar radiation data and historical wind speed observations at 100 m above ground level would greatly enhance the possibility to validate and remove biases from solar radiation and wind speed model projections. Though, currently this type of historical data is difficult to obtain in Brazil. Using the same 3 climate models, future work will examine the impact of climate change on rainfall and streamflow in major hydroelectric river basins in Brazil including the São Francisco, Tocantins, Parnaíba, Xingu, Madeira, and Parana basins.

Acknowledgements

We would like to thank CPTEC - Centro de Previsão de Tempo e Estudos Climáticos/INPE - Instituto Nacional de Pesquisas Espaciais for providing downscaled climate projection data for Brazil and historical rainfall data for the São Francisco basin. We would also like to thank the Brazilian National Council for Scientific and Technological Development/"Conselho Nacional de Desenvolvimento Científico e Tecnológico" – CNPq Brazil (process number 153144/2018-1) for their financial support for this research.

References

[1] K. Jenkins, R. Warren, Quantifying the impact of climate change on drought regimes using the Standardised Precipitation Index, Theor. Appl. Climatol. 120 (2015) 41–54.
[2] T.Y. Gan, M. Ito, S. Hülsmann, X. Qin, X.X. Lu, S.Y. Liong, P. Rutschman, M. Disse, H. Koivusalo, Possible climate change/variability and human impacts, vulnerability of drought-prone regions, water resources and capacity building for Africa, Hydrol. Sci. J. 61 (7) (2016) 1209–1226.
[3] P. de Jong, C.A.S. Tanajura, A.S. Sanchez, R. Dargaville, A. Kiperstok, E.A. Torres, Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability, Sci. Total Environ. 634 (2018) 1540–1553.
[4] C. Fant, C.A. Schlosser, K. Strzepek, The impact of climate change on wind and solar resources in southern Africa, Appl. Energy 161 (2016) 556–564.
[5] D. Carvalho, A. Rocha, M. Gómez-Gesteira, C.S. Santos, Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections, Renew. Energy 101 (2017) 29–40.
[6] V. Ruffato-Ferreira, R. da Costa Barreto, A.O. Júnior, W.L. Silva, D. de Berrêdo Viana, J.A. do Nascimento, M.A. de Freitas, A foundation for the strategic long-term planning of the renewable energy sector in Brazil: hydroelectricity and wind energy in the face of climate change scenarios, Renew. Sustain. Energy Rev. 72 (2017) 1124–1137.
[7] R. Schaeffer, A.S. Szklo, A.F. de Lucena, B.S. Borba, L.P. Nogueira, F.P. Fleming, A. Troccoli, M. Harrison, M.S. Boulahya, Energy sector vulnerability to climate change: a review, Energy 38 (1) (2012) 1–2.
[8] M.P. Pes, E.B. Pereira, J.A. Marengo, F.R. Martins, D. Heinemann, M. Schmidt, Climate trends on the extreme winds in Brazil, Renew. Energy 109 (2017) 110–120.
[9] A. Troccoli, K. Muller, P. Coppin, R. Davy, C. Russell, A.L. Hirsch, Long-term wind speed trends over Australia, J. Clim. 25 (1) (2012) 170–183.
[10] M. Wild, H. Gilgen, A. Roesch, A. Ohmura, C.N. Long, E.G. Dutton, B. Forgan, A. Kallis, V. Russak, A. Tsvetkov, From dimming to brightening: decadal changes in solar radiation at Earth's surface, Science 308 (5723) (2005) 847–850.
[11] M. Wild, D. Folini, F. Henschel, N. Fischer, B. Müller, Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems, Sol. Energy 116 (2015) 12–24.
[12] I. Huber, L. Bugliaro, M. Ponater, H. Garny, C. Emde, B. Mayer, Do climate models project changes in solar resources? Sol. Energy 129 (2016) 65–84.
[13] D. Burnett, E. Barbour, G.P. Harrison, The UK solar energy resource and the impact of climate change, Renew. Energy 71 (2014) 333–343.
[14] MME - Ministério de Minas e Energia/Brazilian Ministry of Mines and Energy, EPE - Empresa de Pesquisa Energética/Energy research company, Balanço Energético Nacional (BEN), Rio de Janeiro, 2018. MME/EPE.
[15] MME - Ministério de Minas e Energia/Brazilian Ministry of Mines and Energy, EPE - Empresa de Pesquisa Energética/energy research company, in: Plano Decenal de Expansão de Energia 2026, MME/EPE, Brasília, 2017.
[16] P. de Jong, R. Dargaville, J. Silver, S. Utembe, A. Kiperstok, E.A. Torres, Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid, Appl. Energy 195 (2017) 538–555.
[17] P. de Jong, A. Kiperstok, A.S. Sanchez, R. Dargaville, E.A. Torres, Integrating large scale wind power into the electricity grid in the Northeast of Brazil, Energy 100 (2016) 401–415.
[18] CEPEL – Centro de Pesquisas de Energia Elétrica/Electricity Research Centre, Atlas Do Potencial Eólico Brasileiro- Simulações 2013, CEPEL, Rio de Janeiro: CEPEL, 2017. Available at: http://www.cresesb.cepel.br/index.php?section=atlas_eolico. (Accessed 20 November 2017).
[19] E.B. Pereira, F.R. Martins, A.R. Gonçalves, R.S. Costa, F.J. Lopes de Lima, R. Rüther, et al., Atlas brasileiro de energia solar, 2.ed, INPE, São José dos Campos, 2017. Available at: http://labren.ccst.inpe.br/atlas_2017.html. (Accessed 27 February 2018).
[20] ABEEólica, Potencial eólico do Brasil é de 500GW. Notícias - Eólica na Imprensa, ABEEólica, 2016. Available at: http://www.abeeolica.org.br/noticias/potencial-eolico-do-brasil-e-de-500gw/. (Accessed 10 May 2018).
[21] A.F.P. Lucena, A.S. Szklo, R. Schaeffer, R.M. Dutra, The vulnerability of wind power to climate change in Brazil, Renew. Energy 35 (2010) 904–912.

[22] E.B. Pereira, F.R. Martins, M.P. Pes, E.I. da Cruz Segundo, A.A. Lyra, The impacts of global climate changes on the wind power density in Brazil, Renew. Energy 49 (2013) 107–110.
[23] P.A. Teixeira, M. Godoi, Potencial técnico de energia solar no país pode chegar a 30 mil GW. CanalEnergia, Rio de Janeiro, 2016. Available at: https://www.canalenergia.com.br/noticias/24686078/potencial-tecnico-de-energia-solar-no-pais-pode-chegar-a-30-mil-gw. (Accessed 10 May 2018).
[24] ANEEL – Agência Nacional da Energia Elétrica/Brazilian National Electricity Agency, BIG – Banco de Informações de Geração/Information Bank of Generation, 2018. Available at: http://www.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.asp. (Accessed 26 February 2018).
[25] F. Maisonnave, Climate Crisis - Northeast: the Present Drought Has Lasted Six Years and Could Become the Norm for Brazil's Semi-arid Region. Folha de S.Paulo, 2018. Available at: http://arte.folha.uol.com.br/ciencia/2018/climate-crisis/northeast/historical-drought-already-lasts-six-years-and-threatens-to-become-rule-in-the-semi-arid/. (Accessed 25 April 2018).
[26] Jornal da Unicamp, Pesquisa aponta alto risco de desertificação na Bahia - Identificação de áreas vulneráveis em polos de produção agrícola serve de alerta para agricultores e representantes do poder público, Universidade Estadual de Campinas, 2018. Available at: https://www.unicamp.br/unicamp/ju/noticias/2018/02/19/pesquisa-aponta-alto-risco-de-desertificacao-na-bahia. (Accessed 25 February 2018).
[27] J.A. Marengo, M. Bernasconi, Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections, Clim. Change 129 (2015) 103–115.
[28] A.R. Neto, A.R. da Paz, J.A. Marengo, S.C. Chou, Hydrological processes and climate change in hydrographic regions of Brazil, J. Water Resour. Prot. 8 (2016) 1103–1127.
[29] J.A. Marengo, R.R. Torres, L.M. Alves, Drought in Northeast Brazil—past, present, and future, Theor. Appl. Climatol. 124 (2016) 3–4.
[30] The World Bank, Low Hydrology Scenario for the Brazilian Power Sector (2016-2030): Impact of Climate on Greenhouse Gas Emissions, The World Bank, Brasília, 2017, 132pp.
[31] S.C. Chou, A. Lyra, C. Mourão, C. Dereczynski, I. Pilotto, J. Gomes, J. Bustamante, P. Tavares, A. Silva, D. Rodrigues, D. Campos, Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios, Am. J. Clim. Change 3 (5) (2014a) 512–525.
[32] S.C. Chou, A. Lyra, C. Mourão, C. Dereczynski, I. Pilotto, J. Gomes, J. Bustamante, P. Tavares, A. Silva, D. Rodrigues, D. Campos, Evaluation of the Eta simulations nested in three global climate models, Am. J. Clim. Change 3 (5) (2014b) 438–454.
[33] MCTI - Brazilian Ministry of Science, Technology and innovation. Secretariat of policies and programs of research and development, in: General Coordination of Global Climate Change. Third National Communication of Brazil to the United Nations Framework Convention on Climate Change – Volume II/Ministry of Science, Technology and Innovation, Ministério da Ciência, Tecnologia e Inovação, Brasília, 2016.
[34] CPTEC-INPE - Centro de Previsão de Tempo e Estudos Climáticos/Instituto Nacional de Pesquisas Espaciais, Plataforma PROJETA - Projeções de mudança do clima para a América do Sul regionalizadas pelo Modelo Eta, 2018. Available at: https://projeta.cptec.inpe.br/. (Accessed 25 April 2018).
[35] BDMEP, Banco de Dados Meteorológicos para Ensino e Pesquisa/Meteorological Database for Teaching and Research, INMET – Instituto Nacional de Meteorologia/Brazilian National institute of Meteorology, 2018. Available at: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep. (Accessed 20 May 2018).
[36] F. Bañuelos-Ruedas, C. Angeles-Camacho, S. Rios-Marcuello, Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights, Renew. Sustain. Energy Rev. 14 (8) (2010) 2383–2391.
[37] X. Zhang, S. Liang, G. Wang, Y. Yao, B. Jiang, J. Cheng, Evaluation of the reanalysis surface incident shortwave radiation products from NCEP, ECMWF, GSFC, and JMA using satellite and surface observations, Rem. Sens. 8 (3) (2016) 225.
[38] D.L. Johnson, R.J. Erhardt, Projected impacts of climate change on wind energy density in the United States, Renew. Energy 85 (2016) 66–73.
[39] C.F. McSweeney, R.G. Jones, R.W. Lee, D.P. Rowell, Selecting CMIP5 GCMs for downscaling over multiple regions, Clim. Dyn. 44 (11–12) (2015) 3237–3260.